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Experimental Study of Upward Forward Smoldering Combustion

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Abstract

An experimental study has been conducted to investigate characteristics of upward forward smoldering combustion of an unretarded polyurethane foam in a forced oxidizer flow. Experiments are done in a small-scale, vertically oriented smoldering cylindrical apparatus. The oxidizer is forced through the igniter which is contact with the bottom surface of foam in a certain volume flow rate. A constant power to igniter is applied until the temperature of foam at 30mm reached 300℃，which make smoldering can propagate itself interior the foam without the aid of igniter. The temperature histories of foam are measured by 14 type-K thermocouples. The gas and condensate released during smoldering are also analyzed by GC and GC/MS respectively. It is shown that the smoldering propagation rate and heat rate of fuel both increase when the smolder front propagates from the bottom of fuel to upper. During the smolder process, concentration of oxygen is below to 0.5%, concentrations of carbon monoxide and carbon dioxide reach up to 5% and 7.6%, respectively. The ruselts also show that more than 73 compounds are identified which including alcohol, ethers and olycyclic aromatic compounds.

Key words: forward smoldering combustion; smoldering propagation; smoke; condensate;

1. Introduction

Smoldering combustion is defined as a self-sustaining, propagating, nonflaming, exothermic, surface reaction deriving its principal heat from heterogeneous fuel oxidation[1]. Smoldering presents a serious risk because the combustion is easy to happen with small heating, and can propagate slowly in the material interior and go undetected for long periods of time[2]. It typically yields a substantially higher conversion of fuel to toxic compounds than does flaming, and may undergo a sudden transition to flaming. According to the American National Fire Protection Association, smoldering are the leading cause of fire deaths in the U.S[3].

Smoldering is often simplied one-dimensional process due to the complexity of smoldeing combustion. There are two basic configurations for one-dimensional smoldering by the relative directions of smoldering propagation and oxidizer flow: forward and opposed[4]. The first study to investigate one-dimensional forward smoldering was that

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of Ohlemiller and Lucca[5] which argued that forward smoldering area included pyrolysis and subsequent oxidation exothermic reaction. a one-dimensional model for forward flow smoldering has been developed by Dosanjh and Pagni[6]. It includes two propagating reation fronts: an endothermic non-oxidative pyrolysis front, and exothermic oxidative char reaction. Schult[7] et al analytically modeled forward smolder with a one-step oxidation reaction using hing activation energy asymptotics. The aim of the experimental research is to investigate the mechanism of one-dimensional upward forward smoldering. An attempt was also made to study the release rate and the characteristics of smoke during smoldering.

2. Experimental system and procedure

A schematic of the experimental setup is shown in fig.1. The experimental appatatus is separated into three parts: smoldering condition system, smoldering reaction system and system of data analysis.

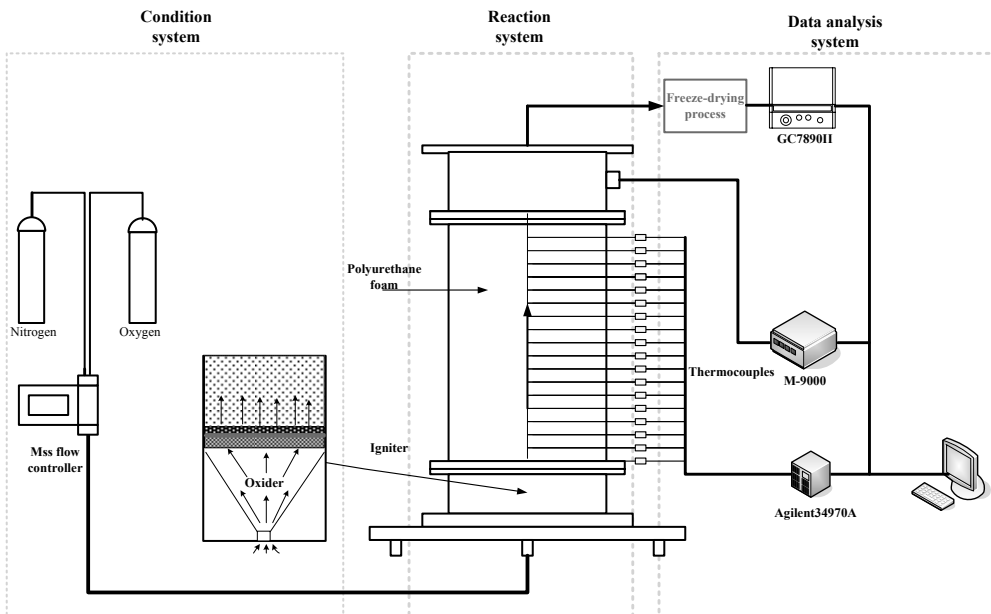

Fig. 1. Schematic of the experimental apparatus setup for the upward forward smolder experiments

In order to attain well-controlled conditons during the experiments, a two-channel gas distribution appatatus is adopted for controlling the internal flow and oxygen concentration of oxidizer through the igniter to analysis the effect of smolder combustion by comparison with a control condition.

The reaction system is conducted in a small-scale smoldering apparatus which is a 400mm long, vertically oriented, 45mm diameter cylinder. The test section uses three-layer insulation to reduce radiation heat transfer which held within a stainless steel frame. The temperature and smoldering propagation velocity are acquired from the temperature histories of one-dimensional arrays of 14 mineral insulated thermocouples (1.0mm diameter) which embedded in polyurethane foam with their junctions along the fuel centerline. Thermocouple 1, 2, 3 are placed at the height of 0mm, 15mm, 30mm from igniter-fuel interface and the other thermocouples are placed at a distance of 30mm each other along the axial line. The igniter consists of an electrically heated resistance wire sandwiched between two porous ceramic disks (45mm diameter 1.5mm thick) that provide rigidity to the igniter as well as diffuse the heat flow. The igniter power is controlled by a transformer regulating AC voltage, and the heat flux conducted from igniter to fuel is measured by DapPRO before experiment.

The data analysis system consists of Agilent 34970 data acquisition. M-9000 combustion gas analyzer, and Techcomp Gas chromatograph 7890A.

The fuel samples are non-fire retarded, open-celled, flexible polyurethane foam. the sample studied is a medium-density foam that is sufficiently permeable to exhibit consistent smoldering behavior. The properties of fule are listed in tablet. 1.

The smoldeirng experimental procedure is as follows: before the smolder experiment, preliminary experiments are carried out with the DapPRO to measure the heat flux on the foam radianting from igniter and the influence of oxidizer velocity on the heat flux, as shown in fig. 2. During the ignition period the AC voltage is kept constant at

Table. 1. Physcial and thermal properties of the unretarded polyurethane foam

property	value
porosity	0.969
permeability	3.857×10^{-10} [m^2]
density of solid	570.46 [kg/m^3]
density of foam	18.968 [kg/m^3]
specific heat of solid	0.938 [kJ/kg-K]
effective thermal conductivity of foam	0.0657 [W/m-K]
effective radiative conductivity of foam	0.0475 [W/m-K]

70V and the oxidizer flow rate is hold at 2.6mm/s in whole smoldering process. Besed on previous experiments, the ignition power is turned off when the temperature of thermocouple 3 reached 300℃ to ensure that smoldering propagation is self-sustained inside the flue. If the temperature is too high, flaming combustion commonly occured on initiation. If the temperature is too low, self-sustained smoldering can not propagate after switching off the power[8]. The voltage signal of thermocouples are acquainted with Agilent 34970 Data Acquisition every three second.

The smoke is acquainted through condensation first and dry. The composition of dried gas is analyzed by Techcomp Gas chromatograph 7890A and the ingredient of condensation is measured by SHI-MADZU GC-MS QP2010plus.

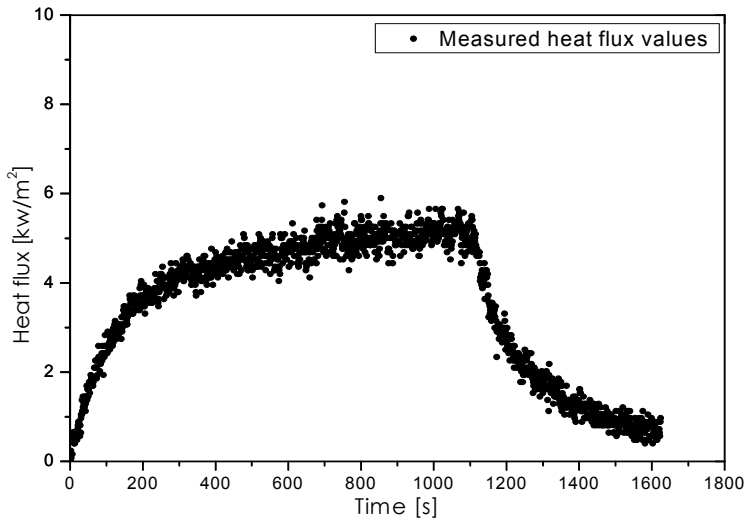

Fig. 2. The picture of heat flux on 70V

3. Experimental study of upward forward smoldering

3.1. The history of temperature change

The temperature history of upward forward smoldering in the soft polyurethane foam is illustrated in fig.3， for a test at forced air velocity of 2.6mm/s and average heat flux of 3.5kw/m2. The igniter is shut off at 528s when the thermocouple 3 at 30mm reached 300℃ to ensure that smoldering propagation is self-sustained inside the flue. The smolder ignition characteristics are determined for the heating time and power data of account, and the temperature histories provided by the thermocouples 1, 2, 3 where on the igniter and foam near the igniter. It is seen that the temperature of thermocouple 1 descend intermediately once switching off igniter, but the temperatures of other thermocouples rise up to 420℃ successively. The result show that the smolder combustion can propagate inside the flexible polyurethane foam in above-mentioned ignition conditons, because the rate of heat release after ignition from smolder reaction is generally higher than the rate of heat losses to the environment.

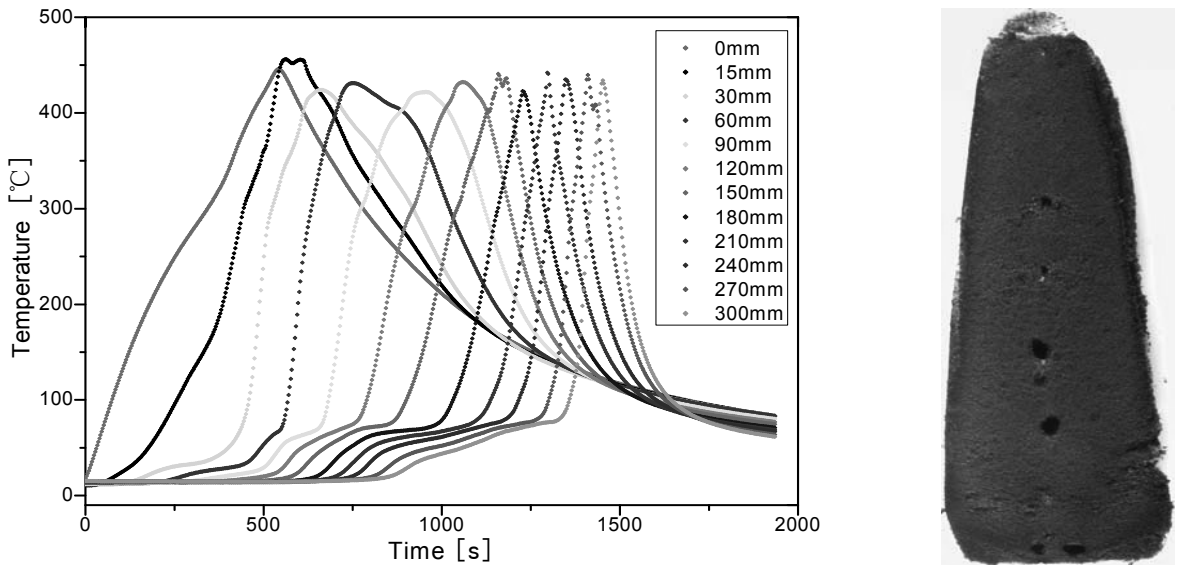

Fig. 3. Thermocouple histories for forced air velocity of 2.6mm/s and cross-sectional view of sample after smoldering

Based on the temperature of thermocouples measured along the foam centre line, the propagation velocity of the smolder front can be calculated from the temperature histories through the distance between two successive thermocouples and the time interval between the highest reaction temperatures, as shown in fig.4. It is seen that the rate of smolder propagation increase to 1.5mm/s from 0.3mm/s with the combustion front propagating from the bottom of fuel to upper. From the simplified theoretical model uses a global energy balance to predict the smolder velocity as a function of the oxidizer mass flux to the reaction, the rate of heat release from smolder reaction is directly proportional to the oxidizer mass flux, and the propagation velocity is then proportional to the heat release rate minus heat losses to environment[9]. The traces of smolder propagation as shown in fig.4 seem to contradict to the above theoretical model at the condition of the oxidizer velocity keeping constantly. In fact, the smolder front propagates is three-dimension and the thermocouples during experiment only probe the temperature histories of foam along the upward centre line. The expermental results showes that the reaction cross-sectional area become smaller when the smolder front propagates from the bottom of fuel to upper.

It is important to make clear thermal decomposition characteristics of polyurethane foam during smolder combustion in this work. With the aid of thermogravimetry analyzer tests in nitrogen and air, it is observed that two main pyrolysis reactions are takeing place in inert atmosphere which the first pyrolysis reaction represents the scission of the poly-isocyanate bond, and corresponds to the less-volatile polyol left behind, and the second step is the polyol further pyrolyzes to ash. During the oxidative degradation process in air atmosphere, the first step is same

as in inert, the successive step is that un-reactional origin foam reactes with oxygen to carbon in higher temperature at about 280℃, the third stage involves the oxidation of the polyol into carbon, the last step consits of the oxidation of carbon into residue. The global kinetic parameters governing the thermal and oxidative degradation of PU are calculated using genetic algorithm, as shown in fig.4. Thus, a five-step mechanism is proposed below:

$$PU \rightarrow v_{dg,p}\,\mathrm{deg}\,raded\;\; PU + v_{g,p}gas$$

$$PU + v_{O_2,o}O_2 \rightarrow v_{cd,o}condensed - phase + v_{g,o}gas$$

$$\mathrm{deg}\,raded\;\; PU \rightarrow v_{rd,dg}residue + v_{g,pdg}gas$$

$$\mathrm{deg}\,raded\;\; PU + v_{O_2,odg}O_2 \rightarrow v_{cd,odg}condensed - phase + v_{g,odg}gas$$

$$condensed - phase + v_{O_2,ocd}O_2 \rightarrow v_{rd,ocd}residue + v_{g,ocd}gas$$

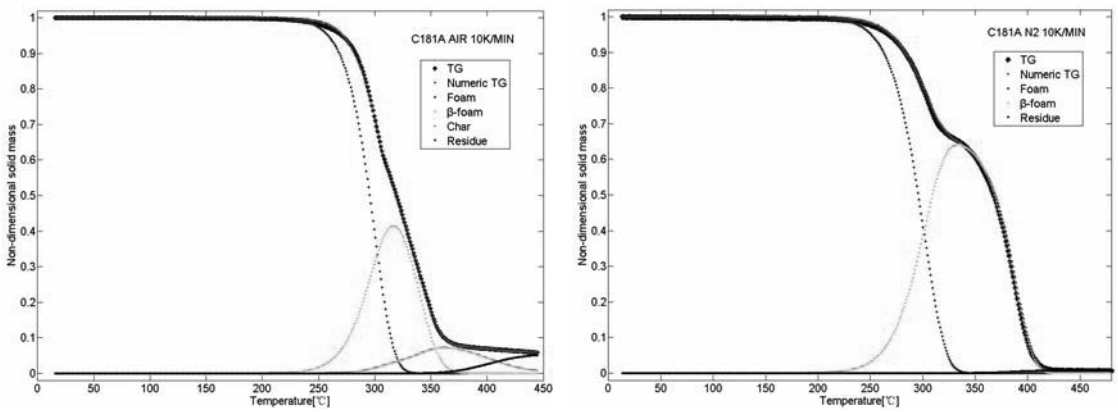

Fig. 4. Comparison of the experimental TG curve of thermal decomposition of soft polyurethane foam with the simulated TG curve with genetic algorithm at the heating rate of 2.5K/min Atmosphere / (a) Nitrogen ; (b) Air

From the above analysis it is seen that the kinetic mechanism of polyurethane foam is very complicated during smolder combustion, especially smoldering often occurs under oxygen-limited conditions. Therefore, a one-dimensional upward forward smolder model has been developed that it includes two distinct propagating fronts: an endothermic non-oxidative pyrolysis front moving first to the virgin fuel and the successive front consisting of a pyrolysis reaction and three exothermic oxidative reactions. With the help of adding heat and oxidizer flow to the virgin foam, some complicated heterogeneous reactions will happen. If endothermic pyrolysis and heat losses to environment is favored over exothermic heat release, the smolder combustion will proceed to extinction. If the exothermic heat release is favored, the smoldering will propagate through the interior of the foam, which consist of two propagating fronts. When the smolder combustion move ahead interior of the foam, products which contained a significant fuel content leave behind. In particular condition, they can continue to react with oxygen which can be more exothermic than the original smolder reaction although more difficult to happen, and make the transition from smolder combustion to flaming.

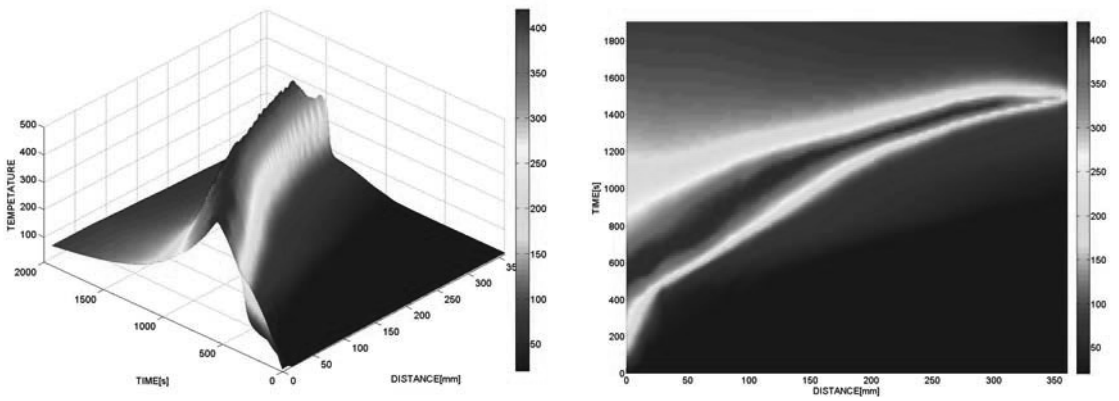

Fig. 5. Three dimensional plot of temperature vs. time vs. distance and aerial view of time vs. distance

The detailed process of smolder combustion is analyzed through the three-dimensional smoldering propagation of waves of temperature vs. time vs. distance, which obtained by using the forward differential fitting method and programming in MATLAB, as shown in fig.5. It is seen that the smolder reaction temperature is low，probably in 420℃, which compared to 900℃ in flamming combustion. The fuel where close to the igniter for 0 to 150mm distance reacts fully because of adding heat from igniter to foam, and the velocity of smolder propagation is 0.3mm/s. But as showen in fig.6, with the combustion front propagating from the bottom of fuel to upperler, the rate of smolder propagation increase to 1.5mm/s from 0.3mm/s. as shown in fig. 6, the temperature rise rate of foam is becoming more and more high when the rate of oxider follow keeps invariantly, and reaction area releasing heat become smaller and heat loss to environment becomes larger. With the smolder front propagating foward, the smolder combustion will proceed to extinction if endothermic pyrolysis and heat losses to environment is favored over exothermic heat release.

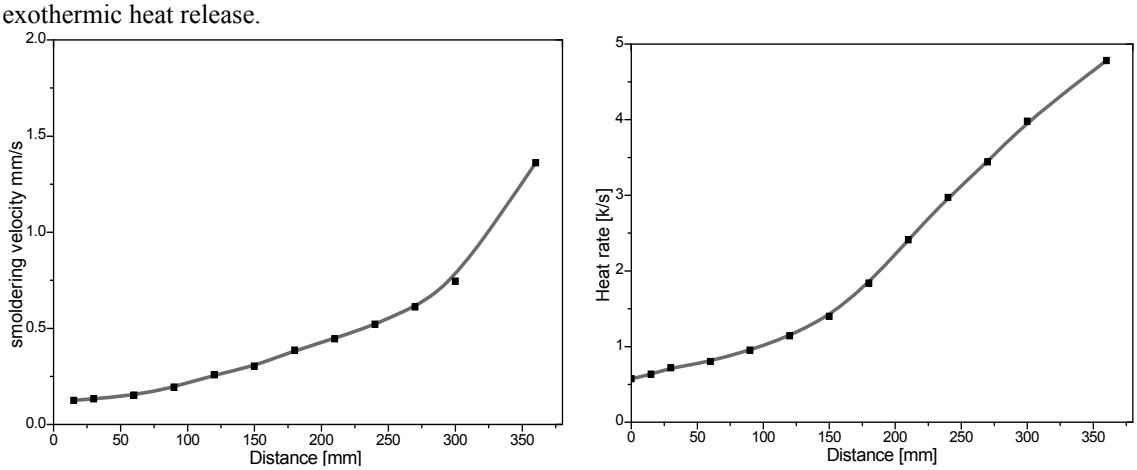

Fig. 6. Variatons of the smoldering propagation velocity (left) and heat rate of foam (right) with distance

3.2. Analysis of gas concentration with time

A gas chromatography method is developed for the analysis of the gas phase of smolder combustion. the contents of oxygen, carbon dioxide and carbon monoxide are calculated using area-external standard method.

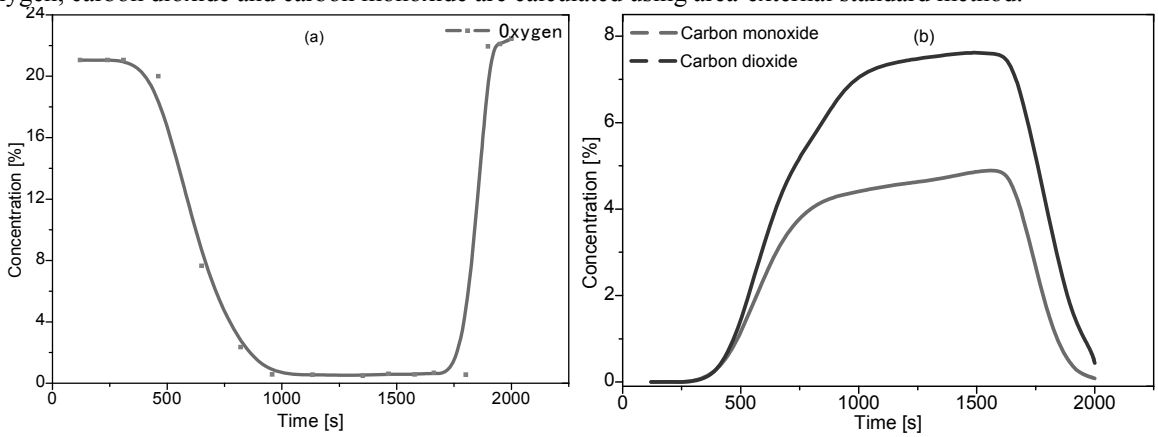

Fig. 7. Variations of gas concentration with time (a): oxygen, (b): carbon monoxide and carbon dioxide

Gas concentration variations with time are shown in fig.7. It is can be seen that as the fuel heats up the temperature near the igniter bellow 200℃, the foam does not react with oxider, then the temperature rises above 200℃, the polyurethane foam pyrolyses intermediately, then the reaction temperature reaches about to 400℃， the concentration of oxygen reduces quickly，this indicat that the smolder combustion begin to react, and with the smolder front propagating from the bottom of fuel to upper, gas concentrations remain steady which concentration of oxygen is below to 0.5%, concentrations of carbon monoxide and carbon dioxide reach up to 5% and 7.6%, respectively.

3.3. Compositional analysis of condensate

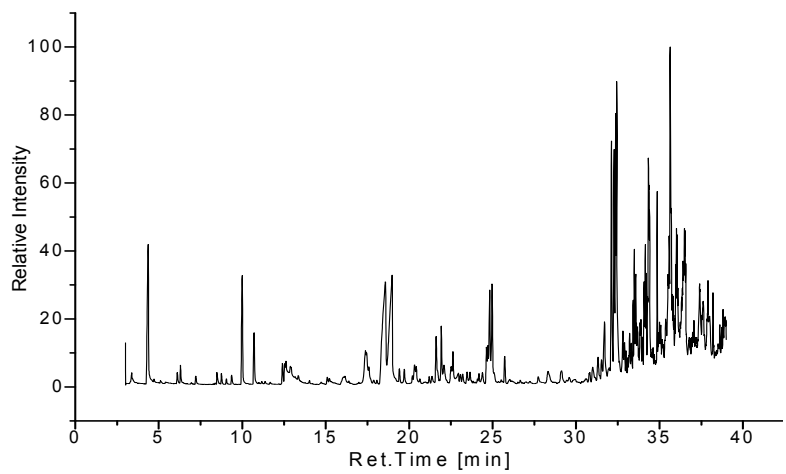

Fig.8. Chromatogram of MS condensate

Compared with the flaming combustion, the somldering is a typically incomplete combustion reaction and produces both the products that would be created in complete combustion and other products. In the present work the various organic constituents of somke condensate from smolder combustion are measured by Shimadzun's GCMSD-QP2010S. The ruselt shows that more than 73 compounds are identified which including alcohol, ethers and olycyclic aromatic compounds. These compounds do great harm to human health as strong carcinogen, metamorphic teratogenic, mutation. Especially the colorless or yellowish polycyclic aromatic compounds with fluorescent characteristic when they are excited, and decompose and metamorphic in the light reaction. Smolder smoke contains a significant amount of organic compounds, that because the smoke condenses to liquid and adheres to the virgin fuel before the combustion area during the smolder front propagating in the foam interior, and then with smolder wave propagating, the condensate and virgin foam pyrolysis and oxidize together, once the smolder front penetrates through the foam upper, a lot of smoke release into environment. Therefore, there has a big differenc in properties of smoke between flaming combustion and smoldering.

4. Concluding remarks

Smoldering is the slow, low-temperature, oxgen limitation, flameless form of combustion, sustained by the heat evolved when oxygen directly attacks the surface of a condensed-phase fuel. Smolder combustion presents a serious fire risk because the combustion can propagate slowly in the fuel interior and go undetected for long periods of times, and produces a significant amount of toxic compounds than does flaming.

Acknowledgements

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